

## Interacting and Merging Galaxies

Uta Fritze - von Alvensleben

*Universitätssternwarte Göttingen, Geismarlandstraße 11, 37083  
Göttingen, Germany*

**Abstract.** I will present a review of some of the many recent developments within the exciting and rapidly evolving field of Interacting and Merging Galaxies. I will touch both on observations and on theory, focussing on those aspects where galaxy evolution modelling may possibly contribute to our understanding.

After briefly outlining the basic concepts and a few specific results of stellar- and gasdynamical modelling of galaxy – galaxy mergers (Sect. 1) I choose three examples of interacting/merged galaxy pairs to discuss different aspects of mergers: tracing back the star formation history of the old merger remnant NGC 7252 (Sect. 2), the formation of young star clusters (Sect. 3) and dwarf galaxies (Sect. 4) in “The Antennae”, and the molecular gas content of IR-UL galaxies on the example of Arp 220 (Sect. 5). I’ll touch the interaction – activity connection in Sect. 6 and report attempts to identify merger remnants among today’s galaxies in Sect. 7. After few words on merger rates at present and in the past (Sect. 8), I’ll close with a brief outlook.

### 1. How it all began...

Arp’s Atlas of Peculiar Galaxies (1966) shows an impressive variety of disturbed galaxies, many of which are evidently interacting or merging. The seminal work of Toomre & Toomre (1972) put forward a whole bunch of ideas which keep stimulating research since more than 20 years. Their basic idea was that the Hubble sequence of galaxies need not be given *ab initio ad infinitum*, i.e. that Hubble types may change in the course of strong interactions. With a restricted 3-body algorithm for an  $N \sim 120$  – body system of particles they modelled the merging of two spirals and showed that the remnant may look very much like an elliptical. Comparing their models to nearby examples of apparently interacting/merging galaxies – most from Arp’s atlas – they established their famous *age sequence of the eleven*. The earliest stage of interaction is represented by Arp 244 = NGC 4038/39 = “The Antennae” and the latest stage of a completed merger by Arp 226 = NGC 7252, both of which I’ll present in some detail in Sect. 2 & 3. Estimating the galaxy merger rate among NGC galaxies they found the number of galaxies that should have experienced a major merger over a Hubble time to be comparable to the number of E/S0 galaxies, thus raising the suspicion that some or even all E/S0 galaxies might be produced by Sp – Sp mergers. Furthermore, they already considered a possible interaction – activity

connection, “*stoking the furnace*”, which I will mention in Sect. 6. From the very beginning, the idea that ellipticals may be built by Sp – Sp mergers has provoked vigorous **Counter-Arguments**, the most famous ones being

- CA 1:** Central densities in ellipticals are much higher than in spirals,
- CA 2:** surface brightness profiles are distinctly different: deVaucouleurs - like in E’s vs exponential in spiral disks,
- CA 3:** the existence of gradients within and of a luminosity – metallicity relation among ellipticals,
- CA 4:** the specific globular cluster (**GC**) frequencies, i.e. the number of GCs normalised to the stellar mass of the parent galaxy  $T_{GC} := N_{GC}/M_*$  (Zepf & Ashman 1993) is roughly twice as high in a typical elliptical as compared to a typical spiral.

Basically, two major **Stellardynamical Approaches** have been developed to model galaxy – galaxy interactions: expansion codes calculating the potential from basis function expansions of the density field (Aarseth 1967 ff, van Albada & Gorkom 1977, ...) and hierarchical TREE codes (Appel 1985, Jernigan 1985, Barnes & Hut 1986, ...) computing the potential from distant groups of particles using low-order multipole expansions. TREE codes have the advantage of being gridless and keeping the action-at-a-distance concept. The number of particles treatable in N-body codes is increasing tremendously in recent years from 250 (White 1978/79, N-Body) over  $10^4$  (Barnes 1988, TREE),  $10^5$  (Hernquist 1993, TREE) to more than  $10^6$  (GRAPE).

Out of the enormous amount of insight these stellardynamical models have provided, I’ll pick a few points that we will need later to understand the observations I’ll present. The nicest tails appear in slow direct encounters in an isolated environment, only disks of comparable mass can produce a pair of equal-length 359ails, up to 25 – 50 % in mass of each disk can get into the tails. Selfgravitating condensations that resemble dwarf galaxies are frequently observed along the tails. Orbital decay efficiently stirs up material in both disks and leads to rapid merging. Violent relaxation (**VR**) is able to produce a deVaucouleurs profile and to make the remnant obey the  $L - \sigma$  relation, i.e. lie in the fundamental plane of elliptical galaxies. VR thus cancels CA 2. Moreover, VR is incomplete allowing gradients to partly survive (cancelling CA 3) and propagates outward, leading to fall-back of material from the tails, only few percent escape. DM halos have been shown to significantly increase the merger cross-section and to considerably accelerate core merging by efficiently soaking up angular momentum. But still if (*Bulge + Disk + Halo*) are selfconsistently included in stellar-dynamical models the central densities of the remnants are much lower than those in ellipticals.

However, observations show enormous concentrations of molecular gas in the centers of interacting galaxies ( $\rightarrow$  Sect. 5) and huge HI envelopes around them (e.g. Sancisi 1995).

**Gasdynamical Models** were developed along three basic streams: **Smooth – Particle Hydrodynamics** (Lucy 1977, Monaghan 1992, ...), a Lagrangian gridless method, made adaptive in space and time by Hernquist & Katz (1989) is

able to treat large density contrasts. In the Sticky Particles method (Negroponte & White 1983, ...) gas particles can dissipate energy in inelastic collisions. Both methods basically confirm and considerably detail the principle results from early (semi-)analytic stability analyses of gaseous disks that perturbations can lead to global instabilities bringing along global and/or nuclear starbursts and eventually create or feed a central black hole (Byrd *et al.* 1986, Lin *et al.* 1988).

Just to pick out of the large number of results from hydrodynamical models a few items relevant to the impact of merging on the evolution of the gaseous and stellar components of galaxies I like to recall that tidal forces in a slow passage are able to perturb gas and stars over the entire disk(s), that shocks efficiently transfer momentum between parcels of gas, and that tidal perturbations, especially in retrograde encounters of gas-rich spirals, can drive a large fraction of all the gas close to the center. During the final collision hydrodynamic forces lead to coalescence of gas blobs and may end up producing **one** massive central gas cloud containing  $\gtrsim 50\%$  of all disk gas (cancelling CA 1). For an excellent extensive review on the dynamical aspects of galaxy interactions the reader is referred to Barnes & Hernquist (1992a).

It is clear that in view of these gas concentrations **Star Formation (SF)** comes into play. Compression of gas clouds by large-scale shocks or a hot surrounding medium as well as precipitation of cloud – cloud collisions are evoked to convert a large fraction of gas into stars on a timescale of order  $10^8$  yr (e.g. Larson 1987, ..., Olson & Kwan 1990, ...). A serious problem for any dynamical model attempting to include SF is that the basic physical processes of SF and the functional dependence of the Star Formation Rate (**SFR**) on gas densities, temperatures, etc. are still poorly understood, in particular for the violent SF regime often encountered in interacting/merging galaxies.

It is clear that massive SF has a significant feedback on the ISM in terms of material and energetics, e.g. in the form of superwinds (Heckman *et al.* 1987, ...). That this feedback may lead to some kind of self-regulation might tentatively be concluded from the similar UV peak surface brightnesses Meurer *et al.* (1996) find in 7 out of 9 starbursts.

Now, let's have a closer look at some famous examples.

## 2. NGC 7252: an advanced post-burst with surprising activity

With an estimated dynamical age of  $\sim 1$  Gyr, NGC 7252 (= Arp 226) (Schweizer 1982ff) is the oldest merger remnant on Toomre & Toomre's list. It features two impressive tidal tails of  $\sim 100$  h $^{-1}$  kpc. 2D VLA HI mapping (Hibbard *et al.* 1993) shows velocity maxima  $\sim$  halfway along the tails containing huge amounts of HI ( $M(\text{HI}) \sim 2 \cdot 10^9$  h $^{-2}$ M $_{\odot}$ ), while the center of the merger remnant is essentially free of HI but harbors a counterrotating disk of ionised and molecular gas ( $M(\text{H}_2) \sim 2 \cdot 10^9$  h $^{-2}$ M $_{\odot}$ ) (Dupraz *et al.* 1990, Wang *et al.* 1992). These observations prompted a new attempt of dynamical modelling where Hibbard & Mihos (1995) use a self-consistent N=65 000-body TREE code describing the gas in two merging (disk+halo) systems and find a prograde initially parabolic encounter to best fit all the available data and featuring a delayed (up to a few Gyrs) fall-back of most of the gas in the tails to successively larger radii within the main body of NGC 7252. As in many other merger remnants, the light dis-

tribution in NGC 7252 follows a de Vaucouleurs law and – despite its impressive merger signatures – NGC 7252 lies unsuspectedly within the fundamental plain of normal elliptical galaxies (Lake & Dressler 1986). Prominent A-star spectral features (Balmer absorption lines) in the nuclear and integrated spectra as well as slightly blue UBV colors that are constant over  $\sim 20$  kpc point to a strong global starburst  $\sim 1$  Gyr ago ( $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  is used throughout).

To study the spectral and chemical evolution of merging galaxies including their starbursts we developed a simplified 1-zone model for the merger of two identical spirals. The 4 parameters of this model are the spectral type (= the star formation history (SFH)) and age of the progenitor spirals and the strength and duration of the tidally triggered starburst. SFHs for undisturbed spiral types Sa, Sb, Sc, Sd were shown to give good agreement after a Hubble time of the model spectra with observed templates from Kennicutt's (1992) atlas. The 4 parameters were studied in terms of 2-color diagrams *UBVR IJHKL* in Fritze – v. A. & Gerhard (1994a). We use this parameter study together with all the available observational data including spectra on NGC 7252 to trace back the SFH of this Sc - Sc merger remnant (Fritze – v. A. & Gerhard 1994b). We find evidence for a strong global starburst that started  $\sim 1.3$  Gyr ago and had a duration of  $\sim 10^8$  yr, and we predict that – if present SF should stop – NGC 7252 would reach typical elliptical galaxy colors within 1.5 – 3.5 Gyr. Instead, however, if the molecular gas disk will be transformed into stars, NGC 7252 may end up as a disk E or even as an S0 galaxy. The nuclear spectrum of NGC 7252 shows  $H_\beta$  emission at the bottom of the deep absorption, HST reveals a strong bluing ( $\Delta(V-I) \sim 0.5$  mag) within the central 200 pc (Whitmore *et al.* 1993) and IUE observations indicate ongoing SF at a rate of  $\sim 4 \text{ M}_\odot \text{ yr}^{-1}$  (Fritze – v. A. & Schweizer, *in prep.*). Our best fit model has a present gas restorage rate from dying (burst) stars of  $\gtrsim 2 \text{ M}_\odot \text{ yr}^{-1}$  which was much higher in the recent past. Moreover, the HI falling back from the tails and not observed within the body of NGC 7252 might, at least partly, be transformed into molecular gas replenishing the reservoir for SF. **In summary**, it looks as if we were witnessing here the evolution of a strong global starburst  $\sim 1$  Gyr ago into a weak central burst still active today and the building up of an appreciable stellar disk in an elliptical-like merger remnant.

On the basis of the progenitor spirals' ISM properties we predict metallicities of stars and star clusters formed in the burst:  $Z \gtrsim \frac{1}{3} \cdot Z_\odot \leftrightarrow [\text{Fe}/\text{H}] \gtrsim -0.8$ . HST detection of a substantial population of Young Star Clusters (YSC) (Whitmore *et al.* 1993) and spectroscopy of the two brightest of them (Schweizer & Seitzer 1993) confirm the high SF efficiency over a large volume of the galaxy ( $R \lesssim 14$  kpc) implied by our high burst strength, our metallicity prediction, the starburst age, and the idea of a central afterburning (Fritze – v. A. & Burkert 1995). With ages  $\lesssim 1.3$  Gyr, most of these YSCs should be globular clusters rather than open ones most of which would already have dispersed.

### 3. NGC 4038/39: Formation of Young Star Clusters

NGC 4038/39 (= Arp 244 = “The Antennae”) is the youngest interacting galaxy pair in Toomre & Toomre's list, an ongoing merger with a starburst that began  $\sim 2 \cdot 10^8$  yr ago. I have chosen it to discuss the HST detection of  $\sim 700$

YSCs (Whitmore & Schweizer 1995), typically a dozen of which, themselves, are clustered within giant HII regions, relics of the supergiant molecular cloud they were born from. This already hints at a molecular cloud structure different from that in the Milky Way ( $\rightarrow$  Sect. 5).

YSCs are seen in many other interacting galaxies/mergers, too: NGC 3597 (Lutz 1991), NGC 1275 (Holtzman *et al.* 1992), NGC 1140 (Hunter *et al.* 1994), NGC 1705 and M82 (O’Connell *et al.* 1994, 95), He2–10 (Conti & Vacca 1994), Cartwheel (Borne 1995), and several examples in Meurer *et al.* (1996).

A sharp controversy is centered on the question if these YSC are young Globular Clusters (**GC**) or rather open clusters/OB-associations. Discriminating properties are the effective radii  $R_{\text{eff}}$  and the Luminosity Function (**LF**) of the YSCs (van den Bergh 1995). Indeed, observations give a wide range of effective radii, however, Meurer (1995) argues that because of crowding of the YSCs on a bright and variable background these effective radii are probably largely overestimated. They estimate the distance out to which effective radii of YSCs can reliably be measured to be  $\sim 9$  Mpc and find that for all 3 galaxies close enough with YSCs detected the mean  $R_{\text{eff}}$  of YSCs are indeed well within the range observed for Milky Way GCs. We model the spectral and photometric evolution of star clusters for different initial compositions ( $10^{-4} \leq Z \leq 2 \cdot Z_{\odot}$ ) and find a strong effect of the metallicity on the color evolution, already at early stages. Knowing the metallicity of a YSC from spectroscopy (or estimating it from the ISM properties at its birth) then allows for quite precise age dating and for the prediction of its future luminosity evolution (Fritze – v. A. & Burkert 1995). The young mean age of  $\sim 2 \cdot 10^8$  yr of the YSCs in the Antennae, for which lack of spectroscopy we can only assume the same metallicity as that of the YSCs in NGC 7252, makes it evident that open clusters may well be co-existent with young GCs. We therefore divide the YSCs into subsamples with large and small  $R_{\text{eff}}$ , cutting somewhat arbitrarily at  $R_{\text{eff}} = 10$  pc because of the above mentioned overestimation. Assuming a common age of  $2 \cdot 10^8$  yr for the YSCs we then evolve the two LFs over a Hubble time and find that they look significantly different. While the LF for clusters with  $R_{\text{eff}} > 10$  pc looks exponential like the LF of Galactic open clusters, the LF for YSCs with  $R_{\text{eff}} < 10$  pc more resembles the Gauss-shaped LF of Galactic GCs with the maximum of the distribution at approximately the correct  $M_V \sim -7.4$  (Secker 1992). However, it features a strong overpopulation in the faint bins (Fritze – v. A. 1995). It is clear that for an ongoing starburst as in the Antennae the age spread among the YSCs should not be neglected. This age spread causes the faint clusters in the present LF to be older on average than the bright ones and, consequently, to fade less over the rest of the Hubble time, moving them to brighter bins in the LF (Fritze – v. A. & Burkert, *in prep.*). Dynamical effects like evaporation through internal stellar mass loss as well as loss of stars and destruction in the inhomogeneous tidal field of the interacting galaxy pair are very difficult to quantify but might preferentially destroy low mass (=low luminosity) clusters.

**Summarising**, I see substantial evidence for the possibility that in gas-rich mergers a significant population of GCs can be formed. These second generation GCs have higher metallicities:  $[\text{Fe}/\text{H}] \gtrsim -0.8$  for mergers of Sb...Sd galaxies that happened not more than 5 Gyr ago. Detection of a bimodal metallicity

distribution in a GC system can prove the Sp – Sp merger origin of the parent E/S0 galaxy long after other suspicious features (tails, ripples, plumes, shells, ...) have disappeared. And if, indeed, GCs form during mergers in numbers comparable to those typical for spirals (Zepf & Ashman 1993), CA 4 is cancelled.

Whatever the nature and future fate of these YSCs, they do trace the dynamical evolution of the starburst through the fact that – on average – they are observed at those galactocentric distances where they were born. Because of easier background subtraction they are much better suited in this respect than the integrated stellar population. A first analysis of radial trends in mean values and rms-scatter of colors, luminosities, and  $R_{\text{eff}}$  are consistent with the scenario of a global starburst contracting with time, like in NGC 7252 (Fritze – v. A. & Burkert, *in prep.*). However, spectroscopy of the YSCs is required to determine precise ages and metallicities before any firm conclusions can be reached. The very youngest star clusters might even allow to explore the upper IMF.

#### 4. Formation of Dwarf Galaxies in Tidal Tails

N-body as well as TREE-SPH models have shown that condensations along tidal tails can form and become self-gravitating with masses typical of dwarf galaxies (Barnes & Hernquist 1992b, Elmegreen *et al.* 1993). Tidal tails contain material from the spiral disks, so these dwarf galaxies will not have DM halos and it is not evident that they will be able to survive the starburst which forms them. The two condensations in Arp 105 studied by Duc & Mirabel (1994) are found to resemble a BCDG and an Im galaxy, respectively. They show [O/H] values typical of outer parts of spirals and  $M/L \sim 1$  inside the optical radius. With luminosities of Im's or BCDGs, these objects resemble *faint blue galaxies*. In the past, mergers were more frequent ( $\rightarrow$  Sect. 8) and galaxies contained more gas, so it may well be conjectured that fading (and dynamically transient?) tidal dwarf galaxies may have to do with the fading of a large dwarf galaxy population invoked to explain the faint galaxy counts, even for  $\Omega = 1$  (e.g. Phillipps & Driver 1995). The gas-rich merging Superantennae (=IRAS 19254-7245) shows a whole chain of dwarf-like objects along its gigantic tails (Mirabel *et al.* 1991). Clearly, more observations are needed to test this hypothesis, in particular spectroscopy to disentangle age and metallicity before the fading can be calculated as well as kinematic information and surface brightness profiles to enable dynamical modelling. A problem, if confirmed, might be the weak clustering of the faint blue galaxies.

#### 5. Arp 220: Molecular Cloud Structure in Gas-Rich Mergers

I choose my 3<sup>rd</sup> example to be Arp 220, an advanced merger and IR-UL galaxy to discuss the Molecular Cloud (MC) structure in massive gas-rich interacting galaxies. Arp 220 has a total  $L_{\text{IR}} \sim 1.6 \cdot 10^{12} L_{\odot}$  with  $2/3 L_{\text{CO}}$  coming from a nuclear disk of  $r \sim 300$  pc and  $1/3 L_{\text{CO}}$  from an extended ( $\sim 5$  kpc) component (Scoville *et al.* 1991). To determine the MC structure in Arp 220 and many other IR-UL galaxies advantage is drawn from the fact that there are submm lines that trace molecular gas at very different densities, e.g.  $\text{CO}(1 \rightarrow 0)$  at  $n \sim 500 \text{ cm}^{-3}$ ,  $\text{HCN}(1 \rightarrow 0)$  at  $n \sim 10^4 \text{ cm}^{-3}$ ,  $\text{CS}(2 \rightarrow 1, 3 \rightarrow 2)$  at  $n \sim 10^5$

$\text{cm}^{-3}$ . HCN observations of Arp 220 (and other IR-ULs) reveal central gas densities  $\rho_0 \lesssim 500 \text{ M}_{\odot} \text{ pc}^{-3}$  comparable to central stellar densities in ellipticals (eg. Solomon *et al.* 1992). The molecular gas dominates the dynamical mass in the centers of these galaxies. On a scale of  $\lesssim 1 \text{ kpc}$ , the core of Arp 220 looks like **one supergiant MC core** and comparison of  $L_{\text{CO}}$  with  $L_{\text{CS}}$  shows that it contains comparable amounts of ultradense and low-density gas ( $\sim 10^{10} \text{ M}_{\odot}$ ), while a giant MC in the Milky Way, the LMC, or a BCDG typically only contains few percent of its total mass at densities visible in CS, i.e. high enough to be transformed into stars. All kinds of SF indicators better correlate with  $L_{\text{CS}}$  or  $L_{\text{HCN}}$  than with  $L_{\text{CO}}$ . SF efficiencies  $\eta$ , i.e. the fraction of the gas mass that is transformed into stars, are also different by up to two orders of magnitude between IR-UL galaxies/mergers ( $\eta \sim 0.1 \dots 0.5$ , Fritze – v. A. & Gerhard 1994b) and spirals/Im’s/BCDGs ( $\eta \sim 0.001 \dots 0.01$ ). Despite some uncertainty in the  $L_{\text{CO}}$ -to- $M(\text{H}_2)$  conversion factor it is clear that the MC structure is drastically different in IR-UL galaxies and other starforming environments. This may rise some doubts as to the universality of the SF process itself. The cloud – cloud collision scheme for SF seems to break down in the dense core of Arp 220. Is there a violent mode of SF realised in massive gas-rich mergers and possibly in an initial collapse as opposed to a peaceful mode now witnessed in spirals, irregulars and even in the comparatively tiny starbursts in BCDGs? To further investigate this question, the study of starburst parameters should be extended to the NIR and applied to samples of interacting and IR-UL galaxies.

## 6. The Interaction – Activity Connection

Optical imaging shows that among the IR luminous galaxies the fraction of interacting systems increases with IR-luminosity from  $\sim 25\%$  for  $L_{\text{CO}} < 10^{11} L_{\odot}$  to 50 – 70% for  $10^{11} \leq L_{\text{CO}}/L_{\odot} \leq 10^{12}$ , and to  $\lesssim 100\%$  for  $L_{\text{CO}} > 10^{12} L_{\odot}$  (Sanders *et al.* 1988, Melnick & Mirabel 1990, Leech *et al.* 1994, Clements *et al.* 1995). While in many cases all of the FIR emission is explained by strong nuclear starbursts with SFRs of order  $100 \text{ M}_{\odot} \text{ yr}^{-1}$  some hyperluminous IR galaxies may also contain a dust-enshrouded AGN (Hines *et al.* 1995, Goldader *et al.* 1995). More than 20 years ago, Searle *et al.* (1973) and Larson & Tinsley (1978) already recognised that the morphologically peculiar galaxies from Arp’s catalogue on average have bluer  $UBV$  colors than normal galaxies and they interpreted these blue colors in terms of enhanced SF activity.

A connection between non-thermal activity and interactions is also found for Seyfert galaxies, many of which are in small groups with a low velocity dispersion and a high spiral fraction, i.e. in an environment most favorable for strong interactions involving gas-rich galaxies (Dahari 1984,...). Some Seyfert galaxies also show tidal tails or close companions (Fricke & Kollatschny 1989, Monaco *et al.* 1994). Circumnuclear starburst and postburst features are detected around an increasing number of Seyfert galaxies (e.g. Genzel *et al.* 1995, Oliva *et al.* 1995) with a possible trend of increasing starburst luminosity with increasing AGN luminosity (Goerdt *et al.* 1993). Hutchings *et al.* (1989) show that  $\sim 70\%$  of the nearby QSOs have close companions. QSO host galaxies often show distorted morphologies, tidal features and/or multiple nuclei (e.g. Stockton & Ridgeway 1991). Dickinson (1995) reports high redshift QSOs to

be located near the centers of galaxy clusters in formation. High redshift radio galaxies are frequently seen to feature dust-lanes, tidal tails and bridges, shells and double nuclei, all of which may point to ongoing or recent interactions.

Thus, it seems clear that **interactions can trigger both thermal (=starburst) and non-thermal (=AGN) activity**. However, there is some strange interaction – activity dichotomy (courtesy K. Borne) in the sense that many active galaxies show signs of interactions while not all interacting galaxies do show signs of activity. A solution to this dichotomy might be that evidence of tidal damage may be long-lived (few Gyr) whereas any form of activity is short-lived ( $\sim 10^8$  yr). This hypothesis is the subject of many ongoing observational and theoretical investigations.

**To summarise:** interactions involving at least one gas-rich galaxy may lead to activity which, in turn, may range from global starbursts (eg. NGC 7252) to nuclear ones (eg. NGC 7714 and many IR-UL galaxies) and to AGNs (QSOs, Seyfert, and hyperluminous IR galaxies). The obvious question is, of course: Is there a transition between these 3 features – either in time or in parameter space (e.g. gas content, velocity dispersion, geometry of encounter, bulge:disk:halo-ratio, ...)? A time evolution from a global towards a nuclear starburst seems indicated in case of NGC 7252 and “The Antennae”, a transition from starburst to AGN activity by observations of circumnuclear bursts/postbursts in Seyfert galaxies, comparable luminosity contributions from starbursts and dust-enshrouded QSOs in case of hyperluminous IR galaxies (Viellet *et al.* 1995) and from observations of comparable CO-luminosities in IR-ULs and QSOs (Barvainis *et al.* 1994, Lonsdale *et al.* 1995).

A severe problem for numerical models is the enormous dynamical range extending from  $\sim 100$  kpc down to  $\leq 10$  pc. A first attempt to bridge all of this range are Bekki’s (1995) TREE SPH models of merging spirals including a simple SF prescription. They show that the orbiting cores *stir up* the gas clouds precipitating SF and that dissipative cloud-cloud collisions are able to drive  $\sim 10^8 M_\odot$  of gas into  $r \leq 10$  pc shortly after core merging. In this model, a **starburst** dominates  $L_{\text{bol}}$  **before core merging** while an accreting **AGN** takes over **thereafter** with retrograde encounters being most efficient in fuelling the nucleus. The low percentage of 8 out of 243 Seyfert galaxies from Véron & Véron (1989) showing double nuclei (Kollatschny & Fricke 1989) is compatible with this scenario of AGN activity occurring in late stages/after completion of a merger.

## 7. Merger Remnants among Present Day Normal Galaxies

It came as a big surprise when a second nucleus 2 pc away from and brighter than the one at the center of the isophotes was detected in Andromeda (Lauer *et al.* 1993, Gerssen *et al.* 1995). Shells and warps reminiscent of past interactions are seen in several spiral galaxies (Schweizer & Seitzer 1988, ...). For the Milky Way, the 2-component GC system, the retrograde halo stars, the Magellanic stream, as well as the thick disk may be indicating past interactions. While Toth & Ostriker (1992) used the existence of a thin disk to limit the rate of satellite accretion, Athanassoula & Bosma (1987) shows that massive halos can stabilise galactic disks considerably so that they can “digest” without damage

up to 10% of their own mass, provided the intruder is not too compact. Hernquist’s models as well as observations of a molecular gas disk in NGC 7252 show that disks can partly be rebuilt after tidal destruction. The prolonged backfall of gas from tidal tails supports this process. Mergers of galaxies with a mass ratio of 3:1 even do leave disk-like remnants in many cases (Barnes 1995). Thus, while among spirals, there is a lot of evidence for past interactions, no statistical analysis of the fraction of nearby spirals having experienced an interaction of a given strength is available.

For E/S0 galaxies, Schweizer *et al.* (1990) define a fine structure parameter  $\Sigma$  meant to somehow quantify the deviation from an “ordinary” appearance and show that the amount of fine structure in a galaxy correlates with its  $\text{EW}(\text{H}_\beta)$  and optical colors in the sense that much fine structure goes with a younger mean age of the stellar population (Schweizer & Seitzer 1992). They give a mean “heuristic merger age” (= time since last major merger) of 5 – 10 Gyr for the E/S0 galaxies from their sample. Peculiar core kinematics as well as disk isophotes are observed in  $\sim 30\%$  of Virgo’s ellipticals (Bender 1995, Skorz 1995). X-coronae are interpreted as coming from hot gas expelled from the galaxy by a starburst-driven superwind (e.g. Fabbiano *et al.* 1989). The levelling-off above luminosities of  $10^{11.5} L_\odot$  of  $\text{Mg}_2$  gradients that increase with luminosity from  $L \sim 10^{10} \rightarrow 10^{11.5} L_\odot$  is taken as evidence for dissipative effects coming into play in the most luminous ellipticals. Hiu *et al.* (1995) report PNe and GCs to significantly rotate around major and minor axes in the outer halo of the dust-lane galaxy NGC 5128 (= Cen A). This outer halo rotation is in agreement with Hernquist’s (1993) prediction for merger remnants. Intriguing coincidences between core mass, core radius, and core density of ellipticals and CO-mass, CO-radius, and gas density in IR-UL galaxies (Doyon *et al.* 1994) may (but need not) point to a Sp – Sp merger origin of many ellipticals. The tightness of the Fundamental Plane (**FP**) is often used as an argument against the merger origin of ellipticals. However, while dissipationless mergers were shown to conserve the FP (Capelato *et al.* 1995), the analysis of E – Sp interactions yields a “FP of changes” that is only inclined by  $15^\circ$  with respect to the observed one (Levine 1995). Lake & Dressler’s (1986) observations of 16 recent mergers from Arp’s atlas show them all to lie perfectly within the FP of normal ellipticals.

**To conclude:** the FP seems to be the result of any violent relaxation process (involving quantities at  $r \leq r_e$  where relaxation is fast) and it is not suitable to test for/against a merger origin of ellipticals. We have, however, already shown in Sect. 3 that the metallicity distribution of a galaxy’s GC system, observable at least up to Virgo cluster distances, does allow to reveal the origin of E/S0 galaxies (see also Zepf & Ashman 1993). In case of a classical monolithic collapse scenario a narrow  $[\text{Fe}/\text{H}]$  distribution is expected for the GC system and tentatively reported by Kissler – Patig *et al.* (1995) for several Fornax dEs. The bimodal metallicity distribution with a secondary maximum around  $[\text{Fe}/\text{H}] \geq -0.8$  predicted for Sp – Sp merger remnants is observed e.g. in NGC 4472, NGC 5128 (Zepf & Ashman 1993), NGC 3923 (Zepf *et al.* 1995), and NGC 3256 (Zepf 1995). For the GCs of cD galaxies with their complex and prolonged merging/accretion history a broad or multiply peaked  $[\text{Fe}/\text{H}]$  distribution is expected as indeed observed e.g. in NGC 1399 (Lee & Geisler 1993).

## 8. Merger Rates

From statistics of nearby galaxy pairs Toomre (1977) estimates a merger rate of  $\sim 0.1 \text{ t}_H^{-1}$ , the recent analysis of Keel & Wu (1995) gives  $\sim 0.33 \text{ t}_H^{-1}$ ,  $\text{t}_H$  being the Hubble time. In the past, merger rates were undoubtedly higher.

Theoretical models based on Press–Schechter formalism with a decoupling from the merging hierarchy predict a redshift evolution of the merger rate  $\sim (1+z)^{4.5\Omega^{0.42}}$  (Carlberg 1990), the CDM halo merging model of Lacey & Cole (1993) also gives a strong increase with redshift with the exact steepness depending on the mass scale involved.

Observations give redshift evolutions of the merger rate as  $\sim (1+z)^{2.5}$  (Toomre 1977 for  $\Omega = 1$ ),  $\sim (1+z)^{4\pm 2.5}$  (Zepf & Koo 1989 from POSS plates and  $\sim 1000$  galaxy redshifts),  $\sim (1+z)^{2.5\pm 0.5}$  (Burkey *et al.* 1994 from HST observations of 146 galaxies to  $I = 26$ ),  $\sim (1+z)^{3.4\pm 1.0}$  (Carlberg *et al.* 1994, 410 galaxies from the CFHT redshift survey to  $V = 22.5$ ), and  $\sim (1+z)^{4.0\pm 1.5}$  (Yee & Ellingson 1995 for 100 galaxy redshifts from the QCRS).

So, despite some quantitative differences, both theory and observations agree in a strong increase of the merger rate to higher redshifts. Significant merger rates in the past are expected to reshape the luminosity function of galaxies, to bring along galaxy number density evolution and to change the Hubble type mix with redshift, as well as to add some extra luminosity during merging-triggered starbursts. Some of these effects have been included one-by-one via simple parametrisations into models for the interpretation of galaxy counts ( $\rightarrow$  eg. Guiderdoni & Rocca – Volmerange 1991, Carlberg & Charlot 1992), a consistent treatment of all effects together, however, has not been attempted until now. Necessary prerequisites for this kind of modelling are to determine local values for burst strengths and durations which we are currently attempting using Liu & Kennicutt’s (1995) sample of interacting galaxies. Still, these values will only apply for low-redshift galaxies, and need not be the same in the early universe where galaxies were much more gas-rich. Furthermore, a better understanding of the longterm evolution of merger remnants (SFRs, rebuilding of disks, ...) as well as of the whole range of interaction events (mass ratios, relative velocities, orbital parameters, etc.) and their effects on the galaxies involved is required.

At any given redshift, the merger rate is expected to depend on environment. Structure formation scenarii (e.g. Kauffmann & White 1993) predict that in low density environments merging should occur later than in high galaxy density regions. This prediction is consistent with deCarvalho & Djorgovski’s (1992) finding that at fixed luminosity field galaxies are bluer, have lower  $\text{Mg}_2$  and higher surface brightness than cluster ellipticals, which can be understood in terms of field E’s being younger than cluster E’s.

How spectacular a merger will look like also depends on environment: Barnes (1992) shows that, within a group or cluster, the tidal forces of the neighbors tend to shred the tidal tails. If only one member of a galaxy pair is gas-rich, the result of a merger might be much less spectacular, both morphologically and spectroscopically, than the famous examples of two gas-rich spirals. In a galaxy cluster at low redshift, the slow encounters favorable for galaxy mergers are very rare, instead, the rapid fly-by’s may also transform Hubble types and

cause starbursts by destabilising gas disks of infalling spirals. These effects of *harassment* are studied e.g. by Moore (1995).

All of these environmental aspects as well as the possibility of multiple mergers (Weil & Hernquist 1996) are important for the discussion of the nature of Butcher – Oemler galaxies in distant galaxy clusters (→ Poggianti, Barger *this volume*).

## 9. Outlook

Only briefly touching some specific aspects of *Interacting Galaxies* I did not at all mention many interesting wavelength ranges as e.g. X-, UV-, NIR- and IRAS observations. I tried to show that dynamical models are in pretty good shape and continuously refined, the major obstacle at present being our poor understanding of the SF process. I hope that interacting galaxies, when carefully analysed with spectrophotometric, dynamical, and chemical models – making use of the young star cluster population – may help improve our knowledge even about star and star cluster formation. We need a solid basis in observations and interpreting models at low redshift. Models attempting to understand high redshift galaxies need to consistently account for all effects related to merging and the possible triggering of starbursts. Galaxy clusters at intermediate and high redshift may provide important clues as to galaxy population, merger rates, etc., provided environmental effects as well as the evolutionary states of the clusters themselves are properly accounted for. A particularly promising approach seems to attempt a combination of galaxy formation scenarii with spectrophotometric and chemical evolution models.

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